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Knowledge as Inventory: Near-Optimizing Knowledge and Power Flows in Edge Organizations (Phase One)

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Knowledge as Inventory: Near-Optimizing Knowledge and Power Flows in Edge Organizations (Phase One)

Abstract
This paper reports on Phase I of a two-phase research project to model, simulate and ultimately optimize knowledge flows in Edge organizations. We begin by describing knowledge as a set of discrete yet perishable skills, and consider how these perishable skills flow through organizations in response to demand triggered by environmental changes. We hypothesize that analyzing the stocks and flows of perishable "knowledge inventory" in organizations, analogous to analyzing those of perishable physical goods inventory in a supply chain, uncovers useful insights to clarify current understanding and permits initial quantification of knowledge management impacts on organizational performance. We examine differences between knowledge and physical goods, and explore how we can adapt methods for costs of knowledge inventory additions, subtractions, reordering as well as EOQ, holding times, inventory doctrines of Just-In-Case, Just-In-Time, and make vs. buy decisions. The discussion leads to the concept of *Knowledge Chain Management (KCM)*. KCM can provide military and business practitioners with a useful framework for maintaining knowledge (and therefore power) levels; and KCM provides a new theoretical lens to frame future research (including our Phase II research) in terms of knowledge and power flows.

Introduction and Motivation

Effective management of scarce resources—particularly knowledge—is critical to mission and project success [6, 8, 14, 28, 38]. Historically, military organizations have tended toward a hierarchical command structure in which high-level knowledge and the global awareness needed to exercise the functions of command and control are achieved centrally at the cost of slower decision making, caused in part by poor distribution and slow movement of knowledge. Current, dynamic military and business environments require much more responsive organization structures that can share information and knowledge seamlessly and rapidly to match organizational flexibility and responsiveness to environmental dynamism.

In *Power to the Edge* [1], Alberts and Hayes describe an agile organizational form whose high level of responsiveness to rapidly changing conditions relies on decomposing command and control by moving power deliberately to the "edge"—the front line of these organizations where they confront and interact with their environments. Alberts denotes *information* as a "dominant factor in the value chain for almost every product or service" [1, p.73]. We extend this notion by defining *knowledge* as information combined with experience that enables action. Therefore, as a point of departure we purport that moving power to the Edge relies on the ability to rapidly move and manage concomitant knowledge. This movement of power and the knowledge to exercise power to the edge, along with mechanisms for the rapid and intuitive flow of information among units, can provide the basis for "shared awareness [1, p. 215]." This in turn enables more "agile" and "robust" organizations, increasingly capable of successful engagement with extremely complex and dynamic environments. Barley indicates that sociological research consistently demonstrates that power resides with the possessor and sender of knowledge over the intended recipient [3]. Although knowledge is just one source of power, it is the focus of our research.

A large body of research exists on *information* flow in organizations, going back to the pioneering work of Herbert Simon in the 1950s [36]. However, the corresponding literature on the flow of *knowledge* in organizations is only just emerging (e.g., [23, 28, 30]) and remains inchoate. To gain theoretical insight into knowledge (and therefore power) flows, we begin by describing knowledge as a set of discrete and perishable skills, and we build upon Inventory Theory (e.g., [19, 31]) to understand how such perishable skills can be made to flow optimally through organizations in response to demands triggered by the environment.

A necessary first step involves conceptualizing stocks and flows of organizational knowledge [11] analogously to stocks and flows of perishable physical goods inventory in a supply chain. This analogy provides useful theoretical insights into knowledge flows and enables initial quantification of knowledge management impacts on organizational performance. Clearly one must take into account differences between knowledge and perishable (or non-perishable) physical goods—e.g., that knowledge stocks or "inventories" are not necessarily diminished by sharing them with others. We also explore how methods for costing knowledge inventory additions, subtractions and reordering speeds can be adapted from Inventory Theory, as well as how *Economic Order Quantity (EOQ)* [5], *Holding Times* and inventory doctrines of *Just-In-Case (JIC), Just-In-Time (JIT)* [39] and *Make vs. Buy* can inform our understanding of knowledge flows. The discussion leads to the concept *of Knowledge Chain Management*. This concept draws by analogy from supply chain management but focuses specifically on the domain of knowledge flows. It offers potential to provide military and business practitioners alike with a useful framework for managing knowledge (and therefore power) levels. It can also provide researchers with an insightful theoretical model to develop new knowledge about knowledge and power flows.

In this exploratory effort, we draw upon the literatures of organizational power [9, 12], knowledge flows [28, 30], inventory control [4, 13], trust and culture [35]. Phase I of the study, which we describe in this paper, addresses development and illustration of *knowledge inventory* and *knowledge chain management* via theoretical modeling. This research does not seek to determine optimal inventory distribution techniques, but analyzes intriguing parallels between perishable goods and knowledge. This effort also does not reach optimization in determining best combinations of knowledge flow, but does explore available alternatives that either increase or decrease dynamic knowledge stores to improve knowledge management.

Phase II of this study will test the effectiveness of different knowledge flow management approaches computationally, using VDT simulation [18, 21, 22] Our computational experiments will be designed to draw insights into promising opportunities and organizational designs for subsequent elaboration and validation in Phase II. In his forthcoming paper to this ICCRTS conference, Nissen examines computational models using a theoretically defined Edge organization [27]. We expect to build upon this work, using many of the same definitions as we continue forward with our line of research.

The balance of this article provides a background into knowledge flows and Inventory Theory. We then present our knowledge inventory management model. This model is illustrated in turn through a practical command and control (C2) application. The article closes with a set of conclusions, managerial implications and topics for future research.

Background

In this section, we discuss key background in knowledge flow and inventory theory.

Knowledge Flow

Polanyi [33] classifies knowledge as explicit versus tacit. Explicit knowledge can be discussed, written, or discretely made manifest. Tacit (or implicit) knowledge is that remaining portion of what is known but which cannot be easily expressed, yet resides in the minds of people. Polanyi illustrates this critical difference, stating that one can observe a person's face for just a few minutes and be able to draw and fully describe that face, yet be unable to provide a complete verbal description. Despite this incomplete description, one is still able to discern that unique face from millions of others because of that remaining knowledge that resides in the mind.

Nonaka pursues this further by advancing the notion that knowledge iterates or "spirals" [30, p. 20] between tacit and explicit dimensions, and over many levels from individual to organizational, thereby becoming reinforced through iterative trial-and-error as in figure 1. For example, Cole [8] purports that explicit forms allow knowledge to transfer or flow from one person or organization to another. In Figure 1, Nonaka illustrates the ontological dimension as the spiral begins first with individual knowledge, advancing though the organizational level, and potentially reaching the interorganizational level.

Nonaka also denotes the phenomena that occur as the spiral continues and knowledge iterates. As noted they consist of *socialization* (creating tacit knowledge through shared experience), *externalization* (conversion of tacit knowledge into explicit knowledge), *combination* (creating new explicit knowledge through extant explicit knowledge), and *internalization* (conversion of explicit knowledge into tacit knowledge – by trial-and-error learning often) [30, p.19].

Before continuing, it is important to render a clear definition of the differences between data, information and knowledge. Data are seen simply as numbers or other symbols without meaning and context. To distinguish information from knowledge, we reference and concur with Hussain's (et al.) paper "Managing Knowledge Effectively" [17], who state that "knowledge is information that is contextual, relevant and actionable, and that it conveys meaning and hence tends to be much more valuable." The discussion concludes stating that "while information as a resource is not always valuable (i.e. Information overload can distract from the important), knowledge as a resource is valuable because it focuses attention back towards what is important" [17, p.2].

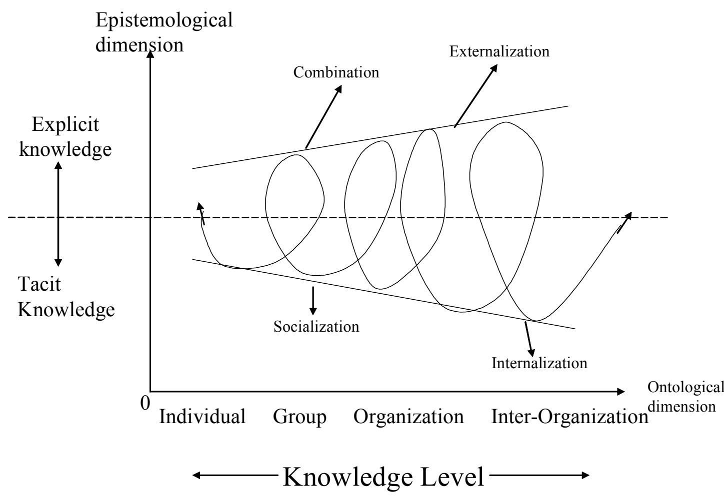

Figure 1: Nonaka's Spiral. Using two dimensions, Nonaka illustrates the iterative process of knowledge creation, showing both the tacit and explicit dimensions of knowledge as well as the ontological dimension ranging from individual to interorganization.

Extending this bidimensional, theoretical framework, Nissen's model of knowledge flow [27] establishes a multidimensional framework for describing and visualizing dynamic knowledge flows by adding a *Lifecycle* and a *Flowtime* dimension to Nonaka's model (see figure 2). *Life Cycle* pertains to the different activities associated with knowledge (e.g., creation, sharing, application) and segments knowledge dynamics into various behavioral modes. Flowtime pertains to the length of time required for knowledge to flow from one coordinate (e.g., person, organization, place, time) to another. Additionally, the terms e*xplicitness* and *reach* are substituted for their counterparts above (i.e., *epistemological* and *ontological*) for clarity. *Explicitness* refers to one's ability to articulate knowledge (e.g., through databases, documents, drawings, conversations) and parses knowledge roughly into explicit and tacit classes; this dimension is homomorphic to *epistemological*. *Reach* considers the level of social aggregation associated with any chunk of knowledge (e.g., number of people sharing it) and divides naturally into common organizational groupings (e.g., individuals, dyads, groups); this dimension is homomorphic to *ontological*.

As delineated by Figure 2, dynamic patterns associated with a variety of different knowledge flows can be described and visualized using these dimensions. Such dimensions are categorical today and do not yet support numerical measurement, except for *flow time* depicted below using arrows of differing thickness to represent respective flow rates. We propose that Nissen's framework can be operationalized to support quantitative measurement of knowledge flows in practice and the development of *near-optimal* path analysis techniques.

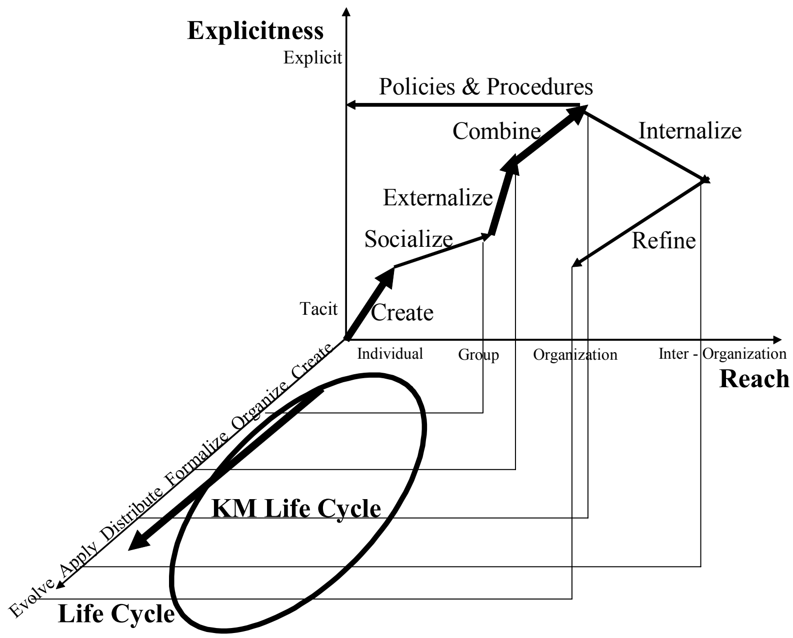

Figure 2: Nissen's Notional Knowledge–Flow Trajectories (2002). Using three dimensions, one can readily plot and robustly discern a variety of diverse knowledge-flow patterns. A fourth dimension indicating flow time is added making the vectors thinner thereby showing a faster path to the next vector in the process.

Nissen's knowledge flow model above takes as its premise that science and engineering each consistently and successfully contribute by informing practice. Precise, explanatory mathematical flow models exist in the physical sciences such as fluid mechanics, electromagnetic wave propagation and light emissions. However, in stark contrast, we are currently hindered by the imprecise and ambiguous, natural language and textual descriptions of knowledge flows [14].

We concede that while illustrating, managing, and quantifying knowledge is challenging, knowledge considered as a collective set of skills held by organizations can be thought of as a finite, but perishable, inventory. This proposed concept of "knowledge inventory" seeks to measure knowledge in both its explicit form such as texts, databases and archives, and its tacit form such as in the minds of persons [33] and routines of organizations [26].

Inventory Theory

Inventories may represent huge investments for the organization [13]. Every dollar invested in inventory represents a dollar that is unavailable for other purposes in the enterprise. Therefore, as an organization builds its material inventory, it must continuously evaluate its market to meet demand and to avoid stock-outs, yet also avoid over-ordering in cases of decreased demand. Balancing these requirements for a complex organization remains difficult at present.

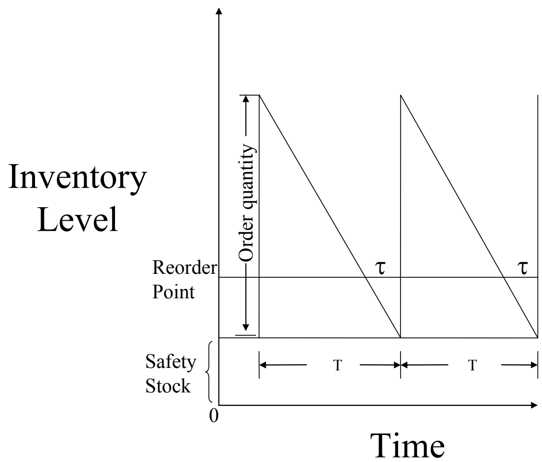

Figure 3: Inventory Model showing inventory levels over a cycle time (T) and considering lead time (τ). The reordering sequence shown allows for the maintenance of a buffer or safety stock [25].

Figure 3 illustrates the changes to inventory level as inventory is expended and reordered. This typical model demonstrates first the immediate arrival of items ordered followed by the gradual, steady decline of on-hand inventory due to item demand. Considering the lead time required to receive items, as well as the desired level of safety stock, more items are ordered and eventually arrive thus increasing the inventory and beginning another cycle.

Operations Research has produced useful theoretical models for inventory management and decision making by providing the manager with closed-form mathematical models to forecast demand, determine best price, maximize profitability, and optimize production levels. Scrutiny of figure 3 above produces the quandary of determining the optimal quantity of items to order that minimizes cost. Economic Order Quantity (EOQ), denoted as Q*, reveals the mathematically optimized "order quantity" to inform the manager how much of an item to order. By ordering according to the EOQ model, the manager is assured of producing *optimal* results [25]. The formula for Q* is shown below.

$$Q^* = \sqrt{\frac{2K\lambda}{IC}}$$

The variables noted are: K (setup or ordering cost of the item), λ (annual demand of the item), I (annual interest rate) and C (the cost to purchase each item). The equation illustrates that as setup costs and demand increase, the amount ordered should also increase. Conversely, as the internal rate of return for the organization and cost of each item (referred to as *holding costs*) increase, the amount ordered should decrease. This formula is very general, usefully applying to a broad array of different physical goods.

As a short example we consider the following given information to determine the EOQ or optimal amount to order. Assume annual demand rate (λ) = 200 units/year, set-up cost (K) = 50 dollars, cost per unit (C) = 10 dollars, and annual interest rate (I) for holding costs = 20 percent. As shown in the equation, Q* equals 100 items to order every time the reorder point is reached.

$$Q^* = \sqrt{\frac{2K\lambda}{IC}} = \sqrt{\frac{(2)(50)(200)}{(.2)(10)}} = 100$$

In the physical realm, phenomena such as customer sales, item perishability and item obsolescence combine to give a close approximation of (λ) found in the EOQ formula above. Additionally, we maintain that parallel losses occur with respect to knowledge as a result of phenomena such as employee turnover, knowledge decay and obsolescence. However, there are at least two ways in which knowledge diverges from physical inventories.

- First, when knowledge is "demanded" in an inventory sense, it can actually increase. Therefore we will refrain from using the term "knowledge demand" but instead refer to "knowledge inventory subtractions" to refer to losses such as employee turnover.
- Second, knowledge also exhibits the trait of a public or "collective good" and exhibits the quality of "jointness of supply" [24]. Knowledge can therefore be used by many people yet not be depleted. In fact, the more it is used, the more it tends to grow!

We discuss these differences in the next section.

In closing this background section and further motivating our research, let us consider the necessary planning to achieve project (or mission) success in terms of worker knowledge. Specifically, most decision makers have at their disposal the ability to determine present worker education and training levels in considering needs and requirements toward accomplishing a new project. This static representation of a list of skill-sets, though seemingly complete, fails to inform the decision maker about how to interpret the future environment. Nor does this kind of static skills inventory, which is included in many ERP systems, provide a means to consider the volatility of the knowledge currently held by workers, or alternative means whereby resources may be most effectively used to add to current knowledge. The next section illustrates the means and necessity of considering methods of adding knowledge, and explores explanations for the subtraction of knowledge. Thus, the decision maker is informed of potential strengths and weaknesses with regard to knowledge inventories, and can therefore make improved use of limited resources such as time and money.

Knowledge as Inventory: A Proposed Model

In a recent Department of Defense presentation given by the Chief of Naval Education and Training, Admiral Harms stated, "The foundation of … effectiveness starts with … having the right skills in the right place at the right time" [16]. Interestingly a quote from Schrady's *Inventory Models: Inventory Theory and Navy Practice*, reads much the same with respect to logistics. "The stated goal is to provide the right material, in the right amount, at the right time, right where it is needed" [36, p.4]. This provides strong motivation to acquire the necessary methods to accomplish with knowledge, what is already achievable in the physical realm.

For many years, inventory management has involved an existing set of formulae that govern and describe its status and process, such as its required levels, associated costs, and optimal ordering as discussed above. However, if knowledge is compared to a perishable good, these same methods and heuristics produce many intriguing insights. Just as with perishable goods, the organization must first determine when, what type, and in what quantity, knowledge must be gained by the organization in order to achieve success in future projects. Further contemplation of knowledge as inventory immediately conjures concerns for the organization such as:

- When to "order" new knowledge;
- Whether the knowledge inventory has been depleted to a point requiring a reorder; and
- How much knowledge should be retained as a buffer or safety stock as in figure 3.

Likewise, available knowledge inventory is affected by personnel turnover (knowledge decreases), environmental changes (knowledge obsolescence), and time (knowledge decay). Table 1 below pairs phenomena of knowledge with their perishable physical goods counterparts.

These concepts and others are elaborated in the following section and are summarized in Appendix A.

Table 1. Knowledge vs. Perishable Goods

Phenomena	Knowledge	Physical Goods
Additions	Mentoring	Custom production (make)
	Formal education	Order (buy)
	Informal training	Job shop production (make)
	On-The-Job training	Assembly line production (make)
	Personnel transfer	Custom order (buy)
Subtractions	Obsolescence	Obsolescence
	Decay	Perishability
	Personnel turnover	Demand
Holding costs	Diffusion benefit	Security, refrigeration, etc.
Optimal Ordering	EOQ	EOQ
Inventory System Operating costs	(about the same)	(about the same)
Operating Doctrines	JIT/JIC	JIT/JIC

Knowledge Inventory Additions (Flows)

In this section we consider methods that increase organizational knowledge inventory—that is, knowledge inflows—the aspects of which include: methods, lead times, expected results, potential costs and savings. Additionally, we discuss their effect in each of the dimensions of *explicitness, reach* and *life cycle* as shown in figure 2 above.

Knowledge inventories are increased through knowledge inflow. Many knowledge flow methods exist such as: mentoring, formal education, classroom training, and On-the-Job Training (OJT). And while each serves to increase knowledge inventory, they do so at different rates and with different characteristics.

Mentoring, for example, provides quick and personalized feedback on errors as well as tailored training, thus enabling faster learning at the individual and potentially group levels. It also has beneficial effects in both tacit and explicit dimensions based on assiduous mentor contact, and because the level of knowledge being transferred is likely highly evolved in terms of *life cycle*. However, mentoring is costly; it assumes that more knowledgeable employees are available and that the organization can function temporarily without them. Mentoring in this instance refers only to that process by which individual transfer of expert knowledge is conducted and does not include other forms such as career planning or counseling.

Alternatively, an employee may be sent to attend **formal education** (e.g., college, Masters, Ph.D). This method yields superb benefits in terms of highly evolved, tacit and explicit knowledge transfer for both the individual and the organization as that knowledge diffuses. However, formal education requires substantial investment in time (lost work) and money (tuition).

To avoid lengthy absences and costly tuition, employees may be **informally trained**. While not as expansive in terms of amount and type of knowledge transferred, it provides a low cost solution toward increasing knowledge in the short term and provides reasonably strong benefits for the organization.

Another low cost method to transfer knowledge at the individual level is through **self-paced study** using books or training software which, although slower, may be fast enough over a long term project and provide modest improvements in explicit and tacit knowledge.

Finally, as a project continues, each employee will simply **learn on the job**, which involves slow transfers of perfunctory knowledge at the individual level and which may also result in many errors along the way.

Alternatively, at its discretion, the organization may identify employees who already have the requisite, or potentially more evolved knowledge, and **assign** them to a specific project temporarily to rectify a lack of knowledge. However, while one project benefits from sudden knowledge increases, another may suffer from the knowledge decrease.

Within the organization, interestingly, knowledge may also be **replicated** - an attribute seldom observed for a physical good. For instance, when knowledge is acquired by one employee within the organization, that knowledge becomes potentially available for all, provided a method exists for its distribution. Even if not deliberately taught to others, as it is used and demonstrated, it tends to propagate or "flow" [8] to other employees and may take new forms, iteratively flowing from explicit to tacit knowledge. Therefore the cost of training just one employee could provide real savings as it is diffused throughout the organization.

We close this analysis with a short discussion concerning the organization's "making" or "buying" knowledge. For instance, as an organization "makes" its own knowledge, it will likely cost more in the short term considering methods such as OJT, which allows for more employee errors and increased time required to learn due to slow knowledge flow. However the organization will benefit over the longer term because that knowledge is maintained by the organization for as long as the employee is retained by the organization. It can also be argued that the kind of knowledge formed through OJT is long lasting and tacit knowledge because the knowledge has been generated by the employee himself [10]. Alternatively, if the organization decides to "buy" its required knowledge through temporary contract workers, it may gain the knowledge more quickly and suffer fewer employee mistakes, however that employee knowledge (and its recent project-based learning) departs the organization—with the temporary workers—at the project's completion. And the worker may unfortunately also be rehired to benefit a rival firm.

Finally when considering knowledge inventory additions, the organization may encounter issue costs. Issue cost, the marginal cost of filling an order is seldom mentioned in formal discussions of procuring inventory due to its proportionately small size [25]. But the cost can be significant for knowledge inventory if an expediting action is required when an organization experiences an "out of stock" condition for a critical knowledge type. Therefore this cost should be considered and appropriately combined with setup costs, if the organization decides to carry low levels of certain knowledge types.

Ultimately, the organization must weigh the unique costs and benefits of each kind of additive knowledge flow as it seeks to increase its knowledge inventory.

Knowledge Inventory Subtractions

Treating knowledge as a perishable good, we next consider methods that serve to decrease knowledge inventories—through knowledge outflows—considering their distinct attributes of: root cause, rate and expected result, while again discussing their differences, using figure 2.

Decreases to available knowledge inventory arise from employee turnover, knowledge decay or knowledge obsolescence. Some researchers argue that organizations do not have memory, but that memory resides in the minds of individuals [41]. Others argue that knowledge accumulates beyond the individual, in organizational routines, for instance Nelson & Winter [26]. Although extending this theory to apply to organizational memory is difficult and subject to debate [22], we deem it appropriate to pursue the means by which employees and organizations decrease their knowledge.

Employee turnover, for instance, causes all individually held knowledge of that employee to be a complete loss to the organization. The causes of employee turnover include market competition, promotion, employment or project termination. This complete loss of knowledge as an employee departs can at times be foreseen, allowing the organization to consider flow alternatives. In terms of *reach*, this loss of available individual knowledge is felt at the group level, and to a lesser extent at the *organization* level, depending on the type and amount of the knowledge lost. The expected result of this total knowledge loss is extra work for others and decreased productivity.

Knowledge decay at the individual level—and arguably also at the group and organization levels—occurs on a much slower scale and is caused by two phenomena – time and interference [2]. Directly stated, *time* causes employees to forget. The rate at which forgetting occurs increases with task complexity and with simple failure to recall an item or procedure with some frequency. Coupled with this is *interference*. Interference considers the number of other tasks that have been accomplished between target events of interest, bumping out portions of the original knowledge. Although decay results in lowered knowledge inventory, it can be remedied through frequent (re)training.

Individuals may fail to *practice* for a relatively long period of time; however, in many domains, through just a small amount of practice we quickly return to the level we reached before [2]. Moreover, in cases of experimental cognitive remembering, once an item has been recalled, it tends to remain neurologically available for some amount of time thereafter [40].

Additionally, knowledge obsolescence can occur due to the volatility or dynamism of the environment and affects all levels of *reach* (individual, group, organization and intra-organization). For example, knowledge of plumbing may remain current for some time because it is slowly changing field, whereas knowledge of software engineering may only remain current for a couple of years due to a more dynamic environment. And knowledge about the stock market might remain current for just a day.

In closing this section of additions and subtractions from knowledge inventory, we need to be aware that knowledge inventory is not merely a “snap shot” of what is held but must be thought of as a dynamic value, always undergoing additions and subtractions [11] and therefore must be carefully managed over time to achieve maximum organizational benefit.

Holding Costs

Within the physical realm, holding costs are those costs associated with maintaining items in inventory, such as security, air-conditioning, and maintenance. However, taken in its two forms of explicit and tacit, knowledge, considered as a perishable good, sometimes exhibits a different set of holding costs. For instance, when compared to that of most physical goods, the marginal cost of adding, duplicating and disseminating explicit knowledge is very low (if not zero). However, in its tacit form, knowledge is much more nebulous to guard and maintain, since it resides in the minds of employees. Therefore the retaining of certain employees with critical or proprietary tacit knowledge becomes a kind of holding cost. Additionally, as tacit knowledge resides in memory, it is subject to knowledge decay and suffers obsolescence if left unused. Therefore, just as the organization must at times remove items from inventory, maintain and update them to keep them up to date, so it must also invoke methods to maintain and update its knowledge inventory. The cost of performing remedies, such as conducting drills or refresher training, to resolve this knowledge atrophy is another kind of holding cost.

Conversely, as employees know more, they may be able to develop novel solutions to difficult problems that they otherwise would not discover solely based on their prior knowledge [7, 15]. Therefore, it seems appropriate to consider that “holding” knowledge contains a hidden *benefit* derived from tacit knowledge stores that enable improved performance.

With regard to *reach* and *life cycle*, the holding costs and hidden benefits discussed above appear to become magnified the further they extend from the center of figure 2. In other words, highly evolved knowledge, along its *life cycle* may decay and become obsolete more rapidly, yet provide much improved problem solving ability. In a similar fashion, reach (referring to the scale from individual through inter-organizational knowledge), is subject to even greater knowledge decay due to time and environmental obsolescence.

In its summation, costs for both tacit and explicit knowledge forms as well as *reach* and *life cycle* must be considered by the organization to predict the cost of holding knowledge inventory accurately.

EOQ (revisited)

For physical inventory, researchers have developed, and practitioners regularly use, Economic Order Quantity (EOQ) to determine the optimal amount of a physical good to order based on known demand, holding and set up costs. This method remains sound provided each term is known with relative certainty. For instance, Brill and Chaouch modeled demand using an exponential distribution in response to uncertain forecasts [5]. Interestingly, although some of the terms may be difficult to predict, the practitioner is comforted knowing that even a 25% error in EOQ results in only a 2.5 percent error in predicted inventory costs [25]. Therefore the method of EOQ is somewhat robust to input variability.

A short, qualitative example illustrates this. First let us consider that the organization requires a certain type of knowledge and can determine the relative magnitude of the input variables. For instance, this particular knowledge may exhibit relatively high knowledge subtractions (demand resulting from decay and obsolescence), relatively low set-up costs (K), and relatively low holding costs (IC). It is seen that a near-optimal amount of knowledge to order (i.e., knowledge flow) will be high. Conversely, as knowledge subtractions remain relatively low due to a static environment, while maintaining relatively equal holding and setup costs, the optimal amount to order is low.

Given the foregoing discussions in earlier sections concerning each of these costs, it seems that as the environment becomes more dynamic, a larger knowledge order (i.e., greater knowledge flow) is needed. Although a seemingly trivial finding, this predictive model uses knowledge flow variable definitions that closely follow a proven method to determine optimal ordering of perishable physical goods with similar output.

Inventory System Operating Costs

Aside from the costs associated with EOQ, the organization may consider the overhead requirements to keep track of its knowledge inventory. For instance, the operation of a physical inventory system includes the data collection system used to determine item demand and procurement lead-time and the cost of making decisions based on such data. This cost is generally static and presents only a small investment once market demand has been established. This remains true until major changes to operating doctrine are considered, such as changes to lead-time, reorder point, and safety stock. Assuming that the current doctrine is satisfactory, this cost is relatively predictable once demand for a particular item is known.

However with respect to knowledge inventory, obtaining the data required to determine knowledge demand could involve considerable human interaction. Accurate predictions of knowledge demand require clear insight into the future requirements of the organization and an accurate knowledge of what the organization currently holds. Because of the many methods to acquire knowledge, combined with their unique lead times, this task is challenging to accomplish but is critical to perform well to optimize the organization's use of scarce knowledge.

Operating Doctrines

Inventory operating doctrines provide the organization a framework to decide when, why, and how often reordering should be accomplished. Two inventory operating doctrines—Just-In-Time (JIT) and Just-In-Case (JIC)—are considered in this section, beginning with an overview of each. This is followed by a discussion of their usefulness in managing knowledge inventories.

Just-In-Time (JIT) began as a Japanese management philosophy chiefly to eliminate waste [25]. Its many beneficial results include reductions in physical inventory, thus saving holding costs and production as well as providing a more flexible organization capable of responding rapidly to changing customer demands. It also leverages the savings found through the use of EOQ ordering. JIT acts as a *pull* system [25, p. 351] using indications such as Kan-ban cards to trigger the next order. Ultimately, JIT seeks to provide resources, parts, and finished inventory just in time.

Just-In-Case (JIC) considers instead the value of slightly increased inventory levels in the event a part may be needed, seeking to avoid costly stock-out conditions. This extra inventory is indeed useful in uncertain environments with unknown demand. Therefore, while JIT seeks to minimize excess inventory, JIC considers the cost versus the potential worth of holding excess inventory. To illustrate this, consider the recent Indonesian tsunami of 2004. The environmental change was unpredicted and those holding surpluses of water and food benefited greatly from their extra inventory. In this case, the value of the JIC inventory far exceeded the cost to hold it.

With respect to knowledge inventory, each policy exhibits both desirable and undesirable traits. JIT seeks to accrue knowledge just as it is needed, thereby saving time and money invested in holding knowledge that is unnecessary and reducing time available for knowledge subtraction via decay and obsolescence. However, if the lead time for a certain type of knowledge is long or unpredictable, this may cause an unwanted stock-out condition which could be difficult and very expensive to remedy. However, if we implement JIT policies for short term, predictable lead time training to counter the effects of knowledge decay, thus providing critical knowledge for a project just as it is needed, this may serve the organization's knowledge purposes well. This is true in the case of dynamic projects whose environments at the beginning may not be known or predictable. Additionally, JIT could be used to represent how the organization distributes its specialist personnel to projects just as they are needed, thus avoiding the cost of educating too many to become specialists.

The operating doctrine of "Just-In-Case" however provides for a "safety stock" [12] of many items to be maintained in the event of unexpected demand. Therefore, an organization may wish to retain some employees with graduate level education in the event that their broad and deep knowledge might become beneficial. Although this policy will intrinsically generate knowledge that may never be used, it may provide flexibility for an organization to respond quickly to unforeseen circumstances and provide the organization with a competitive advantage. Alternatively, implementing a JIC policy organization-wide, whereby all employees are formally and generally educated, would be a very costly proposition. However, there is reason to suspect that at least some of the employees should be generally educated in the event that unforeseen circumstances require their knowledge. Additionally, as more knowledge is held, more knowledge is available for potential diffusion. Therefore, the organization must balance the usefulness of holding many kinds of knowledge to counter the caustic effects of decay and obsolescence.

Many scholars argue that both specialist and generalist knowledge are required to enable organizational success [34]. As predictable but difficult issues are encountered by the organization, the specialist will be needed. However, if the circumstance has never been encountered, the specialist may be unable to solve the issue, whereas the generalist may be able to abstract from similar knowledge to determine the best method to resolve the issue.

Both doctrines are useful at times and must be weighed carefully by the organization. Because of their inherent decentralization, Edge organizations place a high premium on appropriate knowledge distribution and sharing and are highly sensitive to stock-outs of required knowledge. We therefore argue that a combination of JIT and JIC should be considered by the organization to provide near-optimal inventory policies. We postulate that a JIT policy should be followed when the environment is static and can be predicted. However, to the extent that the environment is dynamic and cannot be predicted, the organization should leverage the cost savings of JIT with the supportive policies of JIC.

To close this section, let us consider a practical application of inventory theory toward improving organizational knowledge. Typically, a decision maker wishes to improve organizational knowledge. This may be accomplished intuitively by sending as many individuals as possible to attend formal education (college, Masters, PhD). EOQ, as previously discussed, however, provides the decision maker the optimal quantity to order (individuals sent) by weighing costs versus knowledge inventory subtractions. The decision maker, who desires to increase organizational knowledge, is left with the counter-intuitive solution of sending a limited, though optimal, number of individuals than originally planned. (Eventual knowledge inventory subtractions, however, will allow other individuals to attend formal education in the future.) And although EOQ limits the number of individuals to be formally educated, its use purposefully causes the decision maker to consider alternate means toward increasing organizational knowledge such as: informal training, mentoring, and On-The-Job-Training (OJT). Each of these methods should also be modeled using EOQ to determine optimal numbers of individuals sent. Conducting this kind of analysis will further ensure exploitation of available individual knowledge flows leading toward optimality of organizational knowledge and flow. Such analysis remains beyond the state of the art and practice today. But through research along the lines of this investigation, it has come within sight.

Command and Control Application

Alberts and Hayes offer their Edge organization definition of command and control. *Command* is that which is "involved in setting initial conditions and providing overall intent." *Control* is separate from command: "an emergent property that is a function of the initial conditions, the environment, and the adversaries" [1, p. 217]. Observing that *initial conditions* perform a functional role in both *command* and *control* (C2), and to the extent that they may be altered, we consider one option toward their enhancement.

Watchstanding is a time-honored, core skill that every military organization must excel in to achieve mission success. To improve C2 *initial conditions*, selection of the best flows of knowledge to increase watchteam knowledge and imputed readiness is critical. In considering a ship on deployment, with the understanding that all available personnel are *mission essential*, we will no longer deem formal education as an available option due to time constraints. We therefore limit our scope of available knowledge flows to: mentoring, informal education (training) and OJT as we leverage the use of EOQ, reorder point, safety stock, JIT vs. JIC, and Materials Requirements Planning (MRP) [25] to obtain optimal watchteam knowledge inventory.

The EOQ sections above develop the means to determine optimal knowledge flows. As a deployed ship is considered, we now have greater time constraints coupled with environmental uncertainty. As demonstrated earlier, this will cause our amount of knowledge ordered to increase because of knowledge obsolescence and decay [2]. However, now that we have determined the optimal amount of knowledge to order, we must also consider the level of safety stock desired to avoid a costly stock-out (lack of knowledge) condition. Considering that deployments are arduous and that personnel (and their knowledge) are difficult to replace once they transfer, the lead time required for a watch team to reach proficiency will likely increase because of less time for training. As demonstrated in figure 3 above, this will move our reorder point earlier. Thus, in accord with inventory modeling, and by treating knowledge as a perishable good subject to decay and obsolescence, we not only need to order *greater amounts* of knowledge, but we also need to order it with *greater frequency* as a ship is on deployment.

JIT and JIC inventory policies can also be applied to assist the decision maker in this scenario. JIT seeks to provide knowledge just as it is needed. This is appropriate toward training for a mission that will be conducted with certainty, such as routine watchstanding in a foreign theater of operations. In this case, the threat is known as well as the day of arrival in theater. The best knowledge flow using these criteria is mentoring because, although it requires the time of a mentor, it is also a relatively fast knowledge flow. However as the environment becomes more dynamic, following a JIT knowledge flow policy may not be feasible based on uncertain lead times. In other words, watch teams cannot become immediately proficient in an unforeseen mission, no matter how well mentored. The policy of JIC should therefore be invoked to prioritize training in the order of most likely to least likely missions that the watchteam might encounter. A slower form of knowledge flow such as training is appropriate in support of less likely missions. Additionally, a JIC policy is also appropriate to maintain proficiency in less frequent requirements of generalist-type knowledge such as general damage control. This will enable satisfactory crew performance in a mission that has a low probability of occurrence. Combining training with OJT will provide a sustainable knowledge flow in this instance.

Understanding organizational knowledge inventory also informs the decision maker of the best sequencing of knowledge flows. Material Resource Planning (MRP) is a process used in physical inventories by which plans are made to ensure that earlier ordering and assembly of component parts is conducted ahead of time to ensure that all parts and subassemblies are available for final assembly of a finished, perishable good [25]. We similarly observe that organizational learning must occur in sequence in order to maximize effectiveness. For instance, a newly formed watchteam will not benefit as much from advanced lectures on underwater Doppler equations as they would from basic training on sound propagation. Therefore, a sequence of learning must be adapted to correspond with present knowledge to enable maximum knowledge flow. Interestingly, *absorptive capacity* for new knowledge increases as knowledge levels increase [7]. Subsequently, as a watchteam becomes proficient it can benefit from more advanced and varied training, offered more frequently. The sequence of knowledge flows should therefore begin with OJT, followed by training and mentoring, with recurring repetition of this cycle.

In summary, we argue that proven inventory methods for perishable goods are useful to inform the practice of *command* and *control*. This is accomplished by enhancing an *initial condition* of watchteam knowledge though near-optimal knowledge flows. This approach provides the decision maker a framework to consider the best use of available resources – a critical function of C2. We anticipate increasingly appropriate uses of these methods as our exploration continues in Phase II of our research.

Knowledge Chain Management

In the 1990's a phenomenon took place when the processes of gathering raw materials, manufacturing, ordering, production, inventory, and distribution of goods were considered as one system [19, 25]. The term used to encapsulate this systems approach was *supply chain management*.

Building on the theoretic approach of Nissen [28, 29] as illustrated in figure 2 above, we conceptualize an opportunity to track knowledge inventory from initial knowledge creation (raw material) through its final stage as organization-level, evolved knowledge (finished good). This heuristic approach to knowledge management is termed *knowledge chain management*: knowledge is derived from information (created) and combined with other knowledge (manufactured and socialized), demanded (ordered and externalized) and produced (developed and internalized), inventoried as any physical good and delivered (distributed and refined). By considering the associated costs and benefits, the organization is then able to decide which knowledge, with respect to dimensional *explicitness*, *reach*, and *life cycle*, will best suit its future needs.

Conceptually, we will not attempt to quantify knowledge as a measurable unit, but instead as a percent of what can be known in a specific field of expertise. In considering a percent we must define numerator and a denominator. The numerator is the amount of knowledge held by the individual in a certain field of expertise and is noted as (k). The denominator is the amount of knowledge in the total field and is noted as (K). We consider a beginner's percent of knowledge to be relatively low (eg. 10%), and conversely, an expert's percent of knowledge to be relatively high (eg. 90%). We next consider how each of these variables k and K may change. The rate of change of individually held knowledge (k) is managed by the knowledge additions and subtractions discussed earlier. For instance, k would increase given the type, amount and recency of learning accomplished; however it would decrease due to knowledge decay caused by elapsed time and interference. Field-wide knowledge (K) would also change. As the environment becomes dynamic, more knowledge is created thus proportionally increasing K.

By considering both individual knowledge (k) and field-wide knowledge (K), the organization has a metric of more than just how much knowledge its employees possess, but how that knowledge amount compares to the total knowledge available.

Considering the behavior of individual knowledge (k), we first observe a learning curve as shown in figure 4 below.

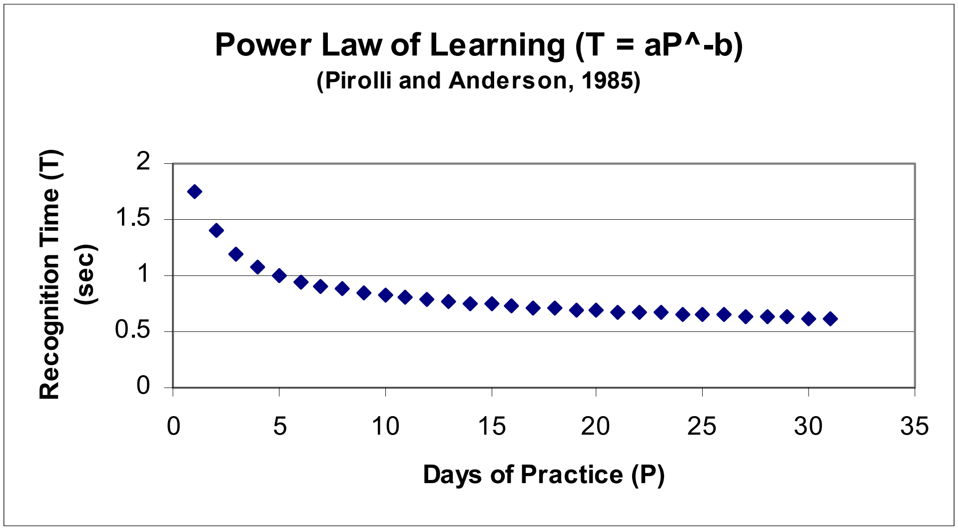

Figure 4: Learning curve showing that time required to perform a task decreases exponentially as the number of days of practice increases [31]

As we expect our knowledge to increase with days of practice, we anticipate modification of the existing curve, illustrating how an individual would progress toward 100% (k/K) as time and learning continues. Figure 5 contains our expected curve that would result from the calculated knowledge metric. The formula attributes denoting a and b are approximated at present for illustrative purposes.

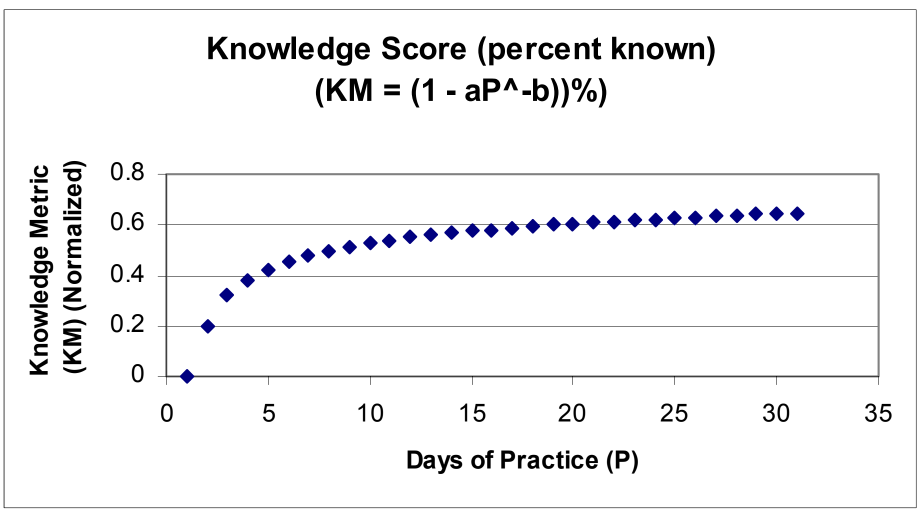

Figure 5: Knowledge Metric graph showing that as practice continues knowledge increases at a decreasing rate subject to the formula shown

Increases in field-wide knowledge (K) would be demonstrated in requiring longer amounts of time to improve upward on the curve in figure 5. From this we postulate that close approximations to k and K will allow us to determine employee and organizational knowledge.

Finally, by using percent knowledge metric (k/K), we can conceive how organizational knowledge flow modeling may be improved using the knowledge metric. If we consider Nissen's knowledge flow model in figure 2 above, and are able to measure knowledge percents along the flow points, we may indeed be able to provide knowledge managers with a useful tool toward illustrating the available organizational knowledge within its knowledge chain. This also has directly beneficial effects in uncoupled command and control within Edge organizations [1] by providing a method for shared awareness of knowledge inventory.

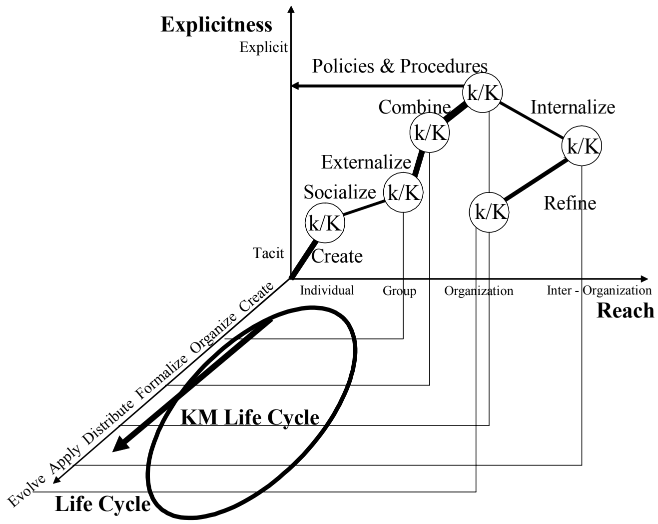

Figure 6: Nissen's Notional Knowledge–Flow Trajectories (2002) shown with k/K at each node, thereby providing knowledge workers a metric to manage their knowledge chain.

Conclusions

Knowledge Management (KM) is largely based on a process of trial and error (mostly error) at present and research is necessary to get beyond current practice. A knowledge inventory research framework based on adaptations and extensions to extant inventory theory appears to afford a promising scientific approach. Once validated and, calibrated, such a theory can provide researchers and practitioners a solid framework to further analyze and understand knowledge management.

The main contribution of this paper is a proposed theoretical knowledge management framework that leverages ideas from inventory control theory and supply chain management. This is a contribution because it offers a novel conceptualization of knowledge flows as being analogous to physical, perishable goods in a supply chain. This article represents a first step in specifying the key variables and variable relations that will be necessary to apply extent inventory models toward knowledge management.

Our long range goal is to inform managers and researchers where deficiencies in knowledge flow exist prior to project commencement and help them to plan in advance for project success by applying principles of Knowledge Chain Management (KCM) derived from a knowledge inventory framework. Progress toward this goal will enable managers to design progressively optimal knowledge management strategies. Near-optimal design outcomes would be a vast improvement over the current state of the art and the state of the practice.

Future Research Plans

Knowing in advance the skills required is of critical importance to any project. However; determining a project's success solely on the basis of knowledge inventory has not yet been accomplished and needs to be supported by research [29]. Phase II of this effort will embed "adapted perishable goods inventory theory" framework for modeling knowledge flows as an extension to existing simulation tools to support modeling of both information and knowledge flows, and will explore contingency approaches for designing organizations to optimize knowledge flows for a variety of task/organizational contexts. Phase II of this effort will leverage organization simulation research conducted by the Virtual Design Team (VDT) research group via a new simulation framework, POW-ER (Project Organization Workflow model for Edge Research). VDT agents have a static knowledge level for each skill type modeled as an ordinal variable (None, Low, Medium, or High) [22]. The POW-ER framework will allow for development of the finer-grained, numerical k/K knowledge metric, and will model and simulate additions and deletions to agents' knowledge as knowledge flows in a knowledge chain.

Conceptualization of knowledge as perishable inventory has already given us new theoretical insights. It also offers potential for immediate practical application toward the management of knowledge. We will continue our exploration of how near-optimization of knowledge and power flows can be enabled and enhanced in both military and business Edge organizations. We expect to contribute toward a more effective practice of knowledge management, and to enhance understanding of knowledge flow phenomena, by extending the capability of computational modeling to reflect knowledge flow in Edge organizations.

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Appendix A – Considering Knowledge as a Perishable Good

The outline below summarizes costs and concerns of considering knowledge as perishable inventory.

1) Knowledge Inventory additions and subtractions
    a. Item costs (C of EOQ formula above)
        i. Additions (Knowledge Flows (Nissen, 2002))
            1. Formal education costs
                a. Tuition
                b. Employee’s salary
                c. Loss of employee (lengthy time away from job),
            2. Informal education (training) costs
                a. Instructor’s pay
                b. Employee’s salary
                c. Loss of employees (short time away from job)
                d. Instruction materials
            3. Simulation or self training costs
                a. Software or books
                b. Employee’s salary
                c. Loss of employee (very short time away from job)
            4. On-The-Job training (OJT)
                a. Potential errors made

                b. Knowledge generated
            5. Hiring or transferring employee
                a. (Placement charge addressed in ordering cost below)
            6. Make vs. Buy Decisions
                a. Organizational decision to create and produce its own knowledge (Make)
                    i. Consider knowledge flows (see inventory additions above)
                    ii. Trial and error
                b. Organizational decision to purchase knowledge (Buy)
                    i. Outsource for consultants
                        1. Knowledge lost at project's end
                    ii. Outsource for databases
                        1. Lesser control of knowledge
        ii. Subtractions (Knowledge Losses) (λ of EOQ formula above)
            1. Employee turnover
                a. Loss of employee knowledge
                b. Loss of employee work
                c. Gain employee salary
            2. Decay (I of EOQ formula above (so far))
                a. Time (forgetting)
                b. Interference
            3. Knowledge obsolescence
                a. Determined by volatility of environment
                    i. Potentially (high, med, low)
2) Economic Order Quantity (EOQ)
    a. How much knowledge to order
    b. Safety stock level based on lead time
    c. Resultant reorder point
    d. Holding Costs
        i. Knowledge Decay
            1. Different levels of decay
                a. Large decay (highly detailed process)
                b. Medium decay (medium detailed process)
                c. Small decay (low detailed process)
        ii. Knowledge archive
            1. Maintenance of archive due to obsolescence
            2. <u>Hidden Benefits</u>
                a. Employees may learn faster and,
                b. May apply learning in novel conditions
    e. Ordering and Set-up costs (K of EOQ formula above)
        i. Manager salary to plan and organize education or training
        ii. New employee placement charge
    f. Shortage (stock-out) costs
        i. Project time lost
            1. All employee's salary (relatively large cost)
            2. Fixed overhead
        ii. Project success
            1. All employee's salary (relatively enormous cost)
            2. Contract profit and incentives
            3. Fixed overhead
3) Inventory Doctrines
    a. Just-In-Time (JIT)
        i. Obtaining knowledge just before it is needed
    b. Just-In-Case (JIC)
        i. Obtaining knowledge in the event it might be needed